ELSEVIER

Earth-Science Reviews 42 (1997) 161–179

EARTH-SCIENCE REVIEWS

Estimates of the Earth's spin (geographic) axis relative to Gondwana from glacial sediments and paleomagnetism

A.G. Smith

Department of Earth Sciences, Downing Street, Cambridge CB2 3EQ, UK

Received 20 May 1996; revised 7 October 1996; accepted 7 October 1996

Abstract

The ice centres of the Permo-Carboniferous and late Ordovician glaciations of Gondwana have been quantitatively estimated. Their positions relative to the inferred mean paleomagnetic poles are not significantly different from those of the Quaternary ice centres relative to the present-day geographic poles. These data suggest it is unnecessary to postulate that the Paleozoic Earth had marked non-dipole components in the geomagnetic field, or that the average of the dipole axis was significantly different from the geographic axis or that there was a significantly different tilt to the geographic axis. The short-lived late Ordovician ice age is tentatively attributed to equally short episodes of faulting within Gondwana. These are believed to have created transient highlands which converted a previously snow-free summer climate into one in which snow could accumulate and build ice caps. Once the faulting ceased the topography decayed and the climate reverted to its previous snow-free summer state. © Elsevier Science B.V. All rights reserved.

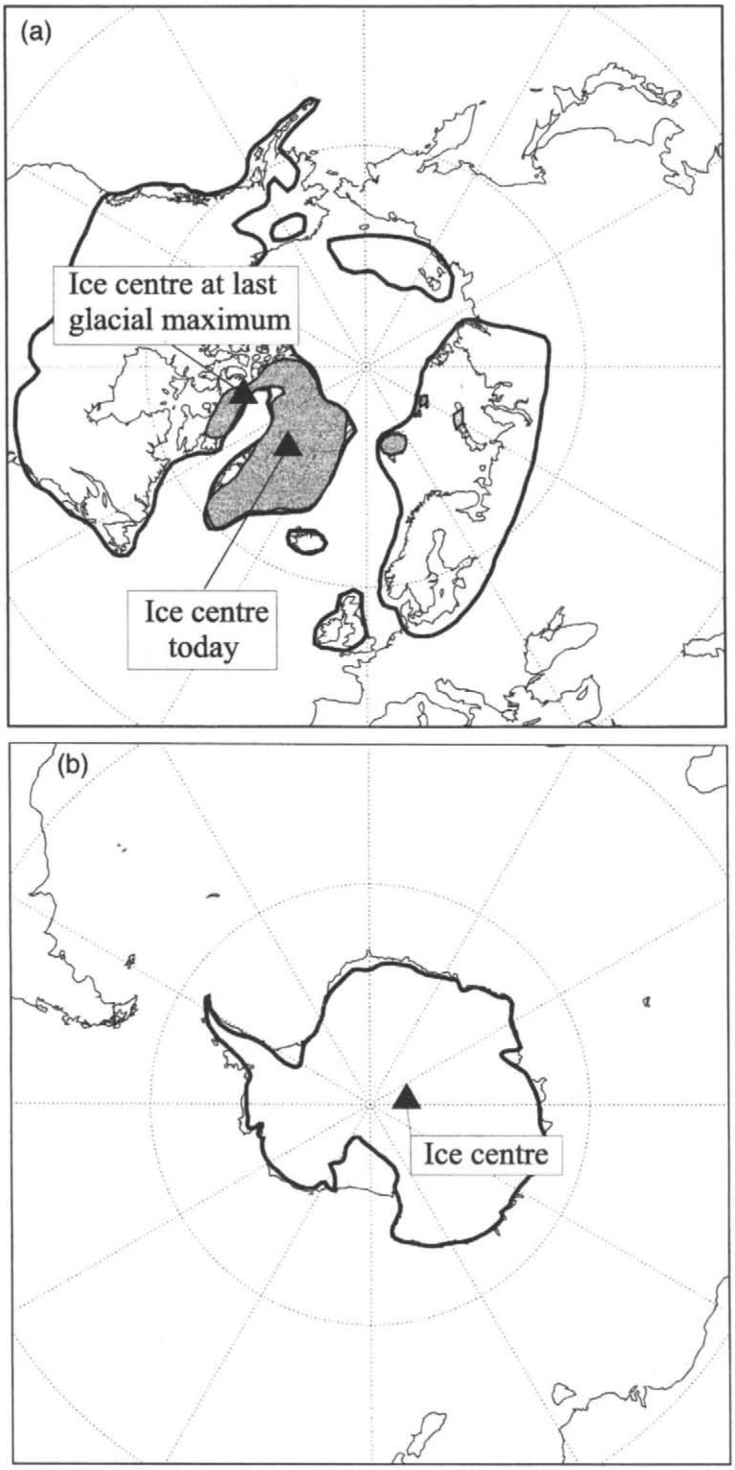
Keywords: tillites; ice ages; paleomagnetism; Gondwana; Paleozoic; Ordovician; Permo-Carboniferous

1. Introduction

Tillites and other glacially derived sediments are well known from the geological record (Hambrey and Harland, 1981; Eyles, 1993). In the Paleozoic era most such sediments are associated with extensive ice sheets analogous to Quaternary polar ice caps rather than the smaller ice sheets associated with lower latitude mountainous regions analogous to the Himalayas. One would therefore expect the bulk of the ice to have lain in high latitudes. Milankovitch frequencies have been recognised in cycles of the late Ordovician to early Silurian Mallowa Salt of West Australia, contemporaneous with glaciation elsewhere (Williams, 1991). They imply that the extent of early Paleozoic ice sheets was also modulated with Milankovitch frequencies in the same way as was the Quaternary ice cover. Analogy with the Quaternary examples suggests that Paleozoic ice sheets may have reached latitudes of 40° during glacial maxima but did not extend further towards the equator.

The former extent of the Paleozoic ice sheets can be inferred from the distribution of Paleozoic glacial sediments, particularly those of sub-glacial origin. However, some paleomagnetic data suggest that Paleozoic ice sheets may have reached much lower latitudes. For example, some of the late Carboniferous to early Permian glacigenic deposits of western South America appear to lie at paleomagnetically estimated latitudes as low as 15° (Veevers and Powell, 1987, fig. 1). Of course, the low Paleozoic

0012-8252/97/$17.00 © 1997 Elsevier Science B.V. All rights reserved.
PII S0012-8252(96)00047-5


(a)
Ice centre at last glacial maximum
Ice centre today
(b)
Ice centre

latitudes may simply reflect the sparse paleomagnetic data available from Gondwanan rocks a decade ago. However, if these results are representative of some Paleozoic examples and if one also assumes a geocentric axisymmetric dipole field, then the low inclinations imply low latitude ice near sea level.

Low latitude ice near sea level appears to have formed in Late Proterozic time, possibly due to a much larger obliquity, or tilt of the Earth's spin axis (Williams, 1994). However, a significant increase in obliquity from its current value of 23.5° to a larger value in Early Paleozoic time is ruled out by an inferred value of 26.4° ± 2.1° at about 430 Ma estimated from the periodicities in the Mallowa Salt and in tidal cycles in the late Precambrian Elatina Formation (Williams, 1993). Low latitude ice may reflect significantly different atmospheric conditions from those of the Quaternary. Alternatively, low latitudes may imply a different geomagnetic field, e.g. one whose axis does not coincide with the spin axis. It therefore seems appropriate to examine the evidence for low inclination ice near sea level during the major Paleozoic glaciations that affected Gondwana during late Ordovician and Permo-Carboniferous time.

Although a great deal is known about Paleozoic glacigenic sediments (Caputo and Crowell, 1985; Eyles, 1993), it is difficult to turn this knowledge into quantitative information about the ice sheets themselves. Probably the most useful information lies in the estimates of the maximum area covered by the ice. If the position of the geographic pole is known, then two useful parameters can be estimated from the geometry of an ice sheet: one, where its centre was in relation to the geographic pole; two, the lowest latitude it reached. These two parameters can be determined for the ice sheets of the Quaternary period and a comparison made with the same parameters for the Paleozoic ice sheets.

The standard method for estimating paleomagnetic errors is to find the value of α_{95} from the distribution of paleomagnetic poles. An α_{95} value implies that there is a 1 in 20 chance that the mean pole lies outside a circle with radius α_{95} degrees drawn around the mean pole. As shown below, the centre of the circle based on present-day global data coincides with the geographic pole, but the centre for data from individual present-day continents may lie several degrees from the pole. The source of this difference is most likely to be due to relatively small non-dipole components in the field, which average to zero when summed for all longitudes. Because Gondwana was a continent of restricted extent, it is necessary to consider the possibility of similar non-dipole effects, which increase the error assigned to estimates of the mean pole based on α_{95} alone.

Thus the question of whether or not the Earth showed significant non-uniformitarian behaviour in late Ordovician and Permo-Carboniferous time in relation to the magnetic field and ice sheet distributions can in principle be answered. If the geometrical properties of Paleozoic ice-sheets are indistinguishable within the limits of error from those implied by the position of the geographic poles estimated from paleomagnetism, then it is unnecessary to postulate non-uniformitarian behaviour at these times; if they are different, then some important features of the Paleozoic world, such as the geomagnetic field, obliquity or atmosphere, were significantly different from those of Quaternary time.

2. Quaternary ice distribution

Antarctica and the Antarctic Peninsula are covered by ice. The centre of the ice-enclosing boundary is near the geographic South Pole, largely because the Antarctic continent is itself is a sub-circular continent centred on the South Pole (Fig. 1b). The co-ordinates of the centre of mass of an area of unit density on a unit sphere, or centroid, is given by:

$$0.5 \times \Sigma \epsilon_{ijk} x_i \mathrm{d} x_j$$

where the sum is taken around the boundary of the

Fig. 1. Ice distribution and ice centres for (a) Northern Hemisphere and (b) Southern Hemisphere. For the northern hemisphere the ice and ice centre at the last glacial maximum are also shown. Note that the ice centres for the northern hemisphere are 15°–17° from the North Pole, reflecting the complex present-day distribution of oceans, ocean currents and mountains. For older periods it is assumed that the centre of the ice distribution could have lain as much as 20° from the geographic pole.

ice. Where several ice areas exist, as in the Northern Hemisphere, the integral is the sum of the integrals for each area. ϵ_{ijk} is 0 if any two of i, j and k are equal. It is 1 if i is not equal to j and j is not equal to k and i, j and k are in cyclic order. It is -1 if i, j and k are not cyclic. x_i are the components of the position vector through the point x, whose coordinates are x_i, x_j, x_k, on the boundary. dx_i is approximated by $0.5 \times [x_i(k) + x_i(k-1)]$, where $x(k)$ is the kth point on the boundary.

For Antarctica the centre of the ice area lies at latitude 85°S and longitude 80°E. The present-day centre of the North Polar ice is in Greenland, at 75°N, 45°W (Fig. 1a). Its position from today back to the last glacial maximum at $21 \cdot 10^3$ yr has been estimated by Peltier (1994). As one goes back in time, the centre remains in Greenland but migrates to about 73°N, 78°W, largely because of the influence of the huge Laurentian and Cordilleran ice sheets. Compared with Antarctic ice, the North Polar distribution is markedly asymmetric, with the centroid of the ice during the last glacial maximum lying 17° from the geographic pole. The asymmetry is clear from the latitudinal extent of the ice: ice reached almost 40°N latitude in North America but did not extend much further south than latitude 70°N in Siberia (Fig. 1a).

Part of this asymmetry is attributable to the Gulf Stream, which kept southernmost Britain, at a latitude 50°, free from ice during the last glacial maximum. Some of the asymmetry must also reflect the irregular distribution of mountainous areas, but the detailed pattern cannot be predicted from general circulation models of the atmosphere because they *require* a knowledge of the distribution of land ice and sea ice as one of their boundary conditions. Peltier (1994) inferred the ice area and thickness from the last glacial maximum at $21 \cdot 10^3$ yr age to the present-day from the way in which ice and water had been redistributed on a viscoelastic Earth as recorded in relative sea level changes at numerous dated sites.

The present-day ice distribution and its evolution since the last glacial maximum illustrate the impossibility of developing simple algorithms for pinpointing former geographic poles from past ice distributions. A semi-quantitative method has been proposed by Scotese and Barrett (1990) in which the latitudinal distribution of paleoclimate indicators, such as tillites, are used as estimators for the positions of past geographic poles. It is difficult to evaluate the errors in such estimates because the data on which they are based have not been published.

Although the distribution of mountains, land and sea was quite different during the late Ordovician and Permo-Carboniferous glaciations of the Southern Hemisphere, analogy with the Quaternary ice sheets suggest that ice is unlikely to have extended equatorward of 40°S and that its centre was no more than 17° from the South Pole. To allow for some error in the geological estimations of the ice sheet boundary, it is assumed here that the centre of large past distributions lay no more than 20° from the geographic pole.

2.1. Estimating ice distributions from glacial sediments

The former existence of ice-caps is established by the recognition of large areas of ancient glacial sediments or of glacially-influenced sediments and the action of former glaciers on the underlying bedrock. Most terrestrial glacial sediments are deposited below ice, at its margins or in ice-dammed lakes. However, after a large ice sheet has melted the distribution of sediment is patchy. In the case of North America, the margin of the former Laurentian ice-sheet is marked by a broad but discontinuous strip of relatively thick till and other areas where the bedrock has been sculpted, grooved and scratched and till is thin or absent (Eyles, 1993). The Cordilleran ice-sheet has left relatively minor till deposits. Moreover, the bulk of North American glacially-produced sediment is marine — about 18 times the terrestrial volume — distributed over the adjacent ocean-floor by submarine fan systems. For example, glacially-produced sediment is a major contributor to the sediment in the Gulf of Mexico.

Pre-Mesozoic glacigenic sediments have been preferentially removed by geological processes: all pre-Mesozoic continental margins and their adjacent ocean-floor and sedimentary cover have been subducted or incorporated into younger active margins. These tectonic processes have destroyed the bulk of the marine glacial record, but since they provide only indirect evidence for the location of the terrestrial ice-sheets, their absence from the geological record is a problem only if most of the other glacial evidence has also been destroyed.

Much of the remaining pre-Mesozoic terrestrial glacial record has been removed by the normal processes of erosion. Only those rocks deposited in unusual settings, such as rift valleys or valleys excavated by the ice itself are likely to be preserved (Eyles, 1993). However, unlike the Quaternary record, much of the pre-Mesozoic glacial record is in the form of glacially influenced *shallow marine, rather than terrestrial* strata. The relationship of these deposits to ice distribution is a matter of current debate (Eyles, 1993).

3. Paleozoic ice ages

The major Paleozoic glaciations are of late Ordovician and Permo-Carboniferous age, with a minor glacial episode in Late Devonian time (Hambrey and Harland, 1981; Eyles, 1993). All are centred on Gondwana, whose general configuration is relatively well-known (e.g. Smith and Hallam, 1970).

Post-Paleozoic deformation exists within Africa in areas such as the Benue Trough in Nigeria and across the South Atlas Fault in Morocco. The magnitude of the deformation is not well known, but in both cases it is unlikely to exceed 100 km, implying that any adjustments to the pole positions are second-order and probably less than the errors introduced by retaining poles from orogenic belts.

The situation in western and southern South America is different. South America today includes several "terranes" that were elsewhere in Paleozoic time: among them are Patagonia, Occidentalia (or the Precordillera terrane) and Chilenia (Ramos et al., 1986). Patagonia is considered to have collided with the rest of South America in Carboniferous time. Occidentalia is an elongate fragment that collided with South America during Arenig–Llanvirn time (Astini et al., 1995). Chilenia is a second elongate fragment that collided with Occidentalia in the later Carboniferous (Astini et al., 1995). The precise extent of Occidentalia and Chilenia is a matter of current debate, but all poles likely to have been on both fragments and on Patagonia prior to their respective collisions have been removed.

A "greater Gondwana" existed in late Ordovician time, with fragments such as north and south China, Sibumasu, Tarim, Qaidam, Lhasa, Qiangtang and possibly Indochina and eastern Malaya joined onto its northeastern margin (Metcalfe, 1992). None of these areas was glaciated in late Ordovician time. Most of these continental areas had rifted from Gondwana by early Carboniferous time, but small continental slivers peripheral to northern India and Australia, such as the Lhasa, Quiangtang and Sibumasu fragments may have been joined to Gondwana during the Permo-Carboniferous glaciation (Metcalfe, 1992). For example, parts of western Yunnan in China were glaciated (Jin, 1994). The positions of these small fragments are still uncertain, as are the Paleozoic positions of parts of western Antarctica and South America.

3.1. Permo-Carboniferous glaciation

Permo-Carboniferous rocks are widely distributed in Gondwana (Fig. 2). The widespread distribution of Permo-Carboniferous glacial sediments in South America, Africa, Madagascar, Arabia, India, Antarctica and Australia (Fig. 3) was one of the major pieces of evidence for the theory of continental drift (Wegener, 1924). Glacial activity spanned virtually the whole of Carboniferous and Early Permian time (Eyles, 1993, fig. 16.1). The ice distribution appears to have been irregular (Crowell, 1983), with mountain glaciers in western South America, a geometrically complex ice sheet in southern Gondwana and other mountain glaciers or small ice sheets in northern India and Australia. The ice was diachronous, with its Carboniferous centre closer to South America and its Permian centre closer to Australia.

In the present state of knowledge it is not possible to make a series of maps showing the maximum extent of ice from early Carboniferous to early Permian time. However, the average distribution of the ice at its maximum extent at ~ 280 Ma is relatively well constrained at both its western and eastern margins (geographic co-ordinates refer to a Gondwana in which Africa is fixed in its present-day position). For example, Eyles (1993, fig. 16.9) shows a detailed map of the extent of the ice-sheet in

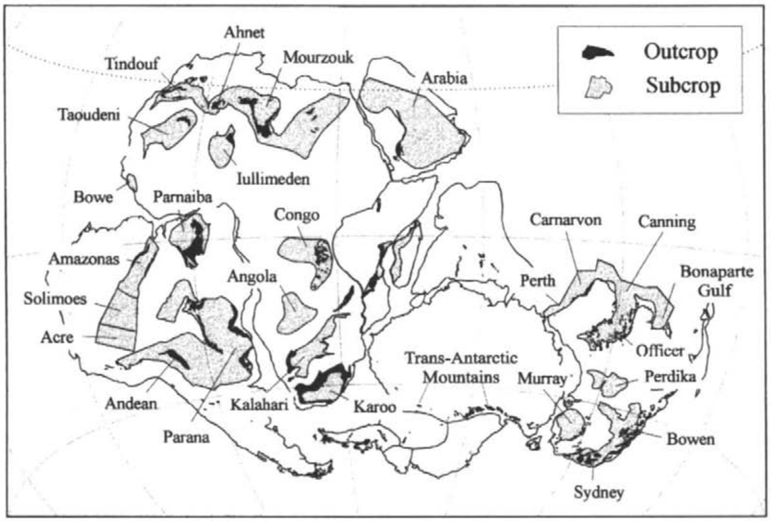


Fig. 2. Gondwana base map, with Africa fixed in its present-day position. The geographic grid (unlabelled to avoid clutter) is drawn at 30° with the equator passing just north of the Congo basin and the Greenwich meridian passing just west of the Iullimeden basin. Except for the unlabelled fragments of Antarctica attached to E. Antarctica (Antarctic peninsula, Thurston Island, Ellsworth block and Marie Byrd Land) only tectonically stable parts of Gondwana are shown, although all stable areas have orogenic belts on their outer margins (see Figs. 7 and 8). Figs. 2–10 use this map as a geographic base. It shows the distribution of Permo-Carboniferous and Permo-Triassic outcrops in black. This has been modified from the UNESCO Geological Map of the World (Choubert and Faure-Muret, 1976). They include rocks labelled as partly or wholly Permian (e.g. Permo-Carboniferous, Permo-Triassic), Carboniferous (in whole or in part) and Upper Paleozoic units. The grey (lightly stippled) areas are basins containing these outcrops. Basin boundaries in N. Africa, Arabia and South America are Early Paleozoic basin boundaries (Fig. 4), which are similar to the younger Permo-Carboniferous basin boundaries. Those in southern Africa and Australia are Permo-Carboniferous basin boundaries. In addition to the UNESCO map, basin boundaries have been taken from Caputo (1985) for Brazil; Veevers and Powell (1987) for Australia and Wopfner (1991) for southern Africa. In a few cases the lateral extent of the basins has been arbitrarily truncated (e.g. Arabia), in others it has been extrapolated from surface outcrop; for some no basin boundaries are shown, as in parts of South America, India and Antarctica.

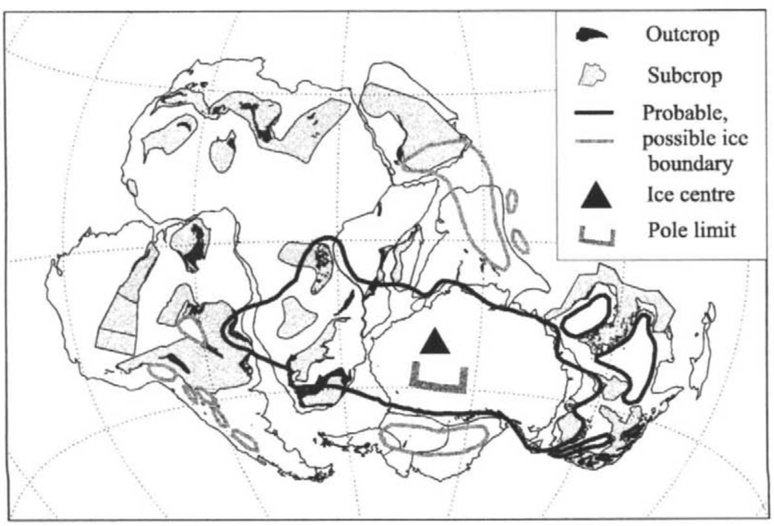


Fig. 3. Extent, centroid and pole limit of Permo-Carboniferous ice. This is Fig. 2 with the addition of ice boundaries in black (reasonably well known) or grey (less well known); the centroid of the ice distribution (black triangle) and a possible limit to the position of the geographic South Pole. The ice distribution is modified from Eyles (1993) and Veevers (1984). See text for discussion of the "pole limit".

southern Africa and easternmost South America in Late Paleozoic ($\sim$ 280 Ma) time. This defines the western boundary of a major ice-sheet with two boundaries running into Antarctica. Detailed maps of the ice at its eastern end in Australia for c. 300–280 Ma have been given by Veevers (1984, fig. 155), with suggested continuations into Antarctica. The two sheets can be plausibly linked together, although if the northern boundary is to continue across southern Madagascar and southern India its boundary in southern Africa must be modified somewhat. The southern boundary is shown as continuing sub-parallel to the Trans-Antarctic Mountains.

More uncertain are the shapes and extent of peripheral ice masses. These were in three areas: western South America, the continental fragments of Antarctica, and India and adjacent areas (Fig. 3). Those in South America have been taken from the schematic distribution of Eyles (1993, fig. 16.2). The ice distribution on what is now western Antarctica is even more schematic, but it is assumed that the Antarctic continental fragments were relatively close to Antarctica and were covered at least in part by ice. The ice distribution in the India–Arabian area also follows that of Eyles (1993).

Detailed work will obviously lead to changes in such an interpretation, but it is unlikely to a radical revision in the gross geometry of the main ice sheet, whose centre is at 23°S, 47°E. The centre of all the ice masses is only 4° away at 21°S, 50°E.

The Permo-Carboniferous ice sheet is so extensive that it can only just be fitted within a latitude circle of 50° (not illustrated). If all of it is of the same age, an unlikely but necessary assumption, then the centre of the visually best-fitting circle is at about 30°S, 47°E. If the centre is moved more than about 5° W then some of the Australian ice lies at latitudes lower than 40°; if it is moved more than about 5° E, then some of the South American and Dwyka ice in southern Africa is moved into latitudes lower than 40°. The centre of the circle can be moved north, but a more southerly position puts some of the ice in Oman into lower latitudes. The constraints imposed by the ice distribution are shown as the "pole limit" symbol in Fig. 3. A pole of 30°S, 47°E is considered a reasonable estimate for the geographic pole during maximum glaciation, with an uncertainty of at least 5°.

3.2. *Late Devonian glaciation*

Devonian glacigenic sediments are known in outcrop principally in Brazil from the Cururi Formation of the Amazon Basin and the Cabecas Formation of the Parnaiba Basin (Caputo, 1985). Their glacial origin has been a matter of debate (Rocha-Campos, 1981a,b) which now appears to have been settled (Caputo, 1985). The correlative Jaraqui Formation of the Solimoes Basin is known only in subcrop and also has features suggesting a glacial origin (Caputo, 1985). All three formations are relatively well-dated as Famennian ($\sim$ 365 Ma). Though the glacial origins of the Cururi and Cabecas Formations have been established, their precise depositional setting is unclear. Glaciomarine sediments of Late Famennian to Early Tournaisian age are known from the Cuman Formation of Bolivia in the Titicaca basin. Their sedimentological significance is currently being reexamined (Eyles, 1993, p. 131). Possible glacial sediments of Devonian age or, more probably, Early Carboniferous (Tournaisian) age are known from the Iullimeden basin in Niger (Hambrey and Kluyver, 1981).

The Late Devonian sediments of South America do not appear to be the remnants of sub-glacial deposits formed under a large continental ice-sheet. Rather, many of them seem to be glacio-marine deposits sourced from mountain glaciers on the western edge of South America or from small ice caps formed on massifs within South America (Eyles, 1993, p. 132). Because the ice distribution that gave rise to them is not known and the ice itself appears to have been on a much smaller scale than the Late Ordovician and Permo-Carboniferous examples, their relation to the paleomagnetic pole is not discussed.

3.3. *Late Ordovician glaciation*

Ordovician outcrops are well known in South America, Africa, Arabia and Australia (Fig. 4). The Late Ordovician glaciation of Gondwana left a swathe of deposits in the Ordovician basins of northern Africa, Arabia, southernmost Africa and South America (Hambrey, 1985; Fig. 5). Old glaciated valleys filled with till are known from Saudi Arabia

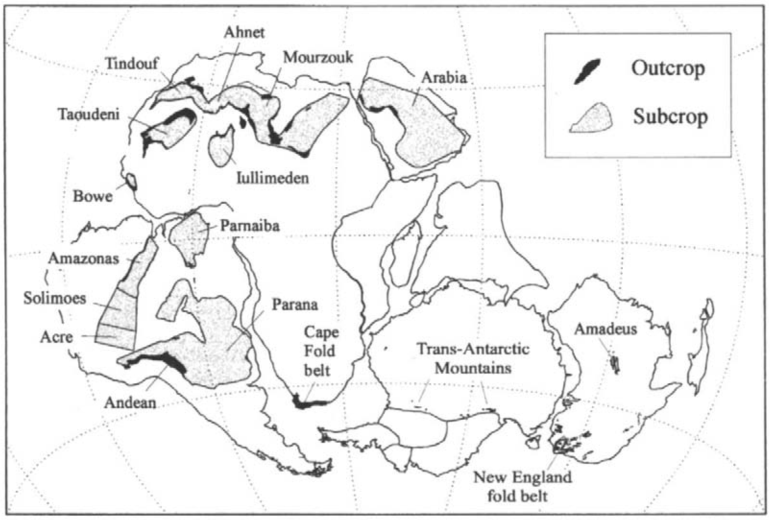


Fig. 4. Distribution of Ordovician outcrops (black) plotted on the Gondwana base map of Fig. 1 from the source given in Fig. 2. They include rocks labelled as partly or wholly Ordovician. The grey (lightly stippled) areas are the major Ordovician basins containing these outcrops. In addition to the UNESCO map, basin boundaries have been taken from Caputo (1985) for Brazil. In a few cases the lateral extent of the basins has been arbitrarily truncated (e.g. Arabia), in others it has been extrapolated from surface outcrop; for some no basin boundaries are shown, as in parts of W. Africa, Australia and Antarctica.

(Vaslet, 1990). Glaciated pavements and associated deposits occur in several basins in north Africa: in Morocco in the Tindouf basin (Destombes, 1981); in West Africa in the Taoudeni basin (Deynoux and Trompette, 1981); in the Hoggar region of the central Sahara (Biju-Duval et al., 1981). A summary of

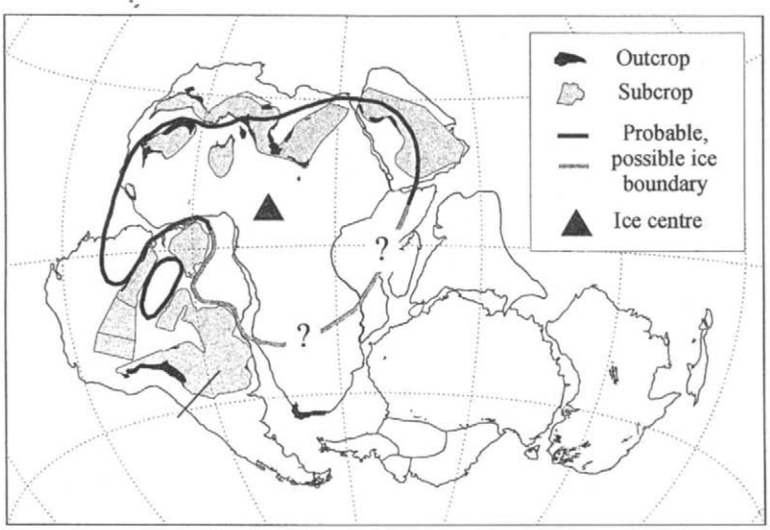


Fig. 5. Extent and centroid of late Ordovician ice. This is Fig. 4 with the addition of ice boundaries in black (reasonably well known) or grey (less well known) and the centroid of the ice distribution (black triangle). The ice distribution is principally that of Vaslet (1990) with modifications. See text for details.

West African glacial features is given by Deynoux (1985, fig. 3). The depositional setting of the isolated southern African occurrence, dated as latest Ordovician to early Silurian (Rust, 1981) is unclear (Eyles, 1993, p. 122). Although ice appears to have folded and deformed the underlying sediment on a large-scale (Bell, 1981; Rust, 1981; Visser, 1989). It has been omitted from Fig. 5. Diamictites characterise the South American deposits (Crowell et al., 1981; Rocha-Campos, 1981c; Grahn and Caputo, 1992), some of which may be sub-glacial, though once again their precise depositional origin is not known (Eyles, 1993). Most may be periglacial, marginal to ice sheets on the adjacent Guyana and Brazilian shields (Eyles, 1993).

Early Paleozoic glacial sediments are not known from Australia or Antarctica. Possible glacial sediments, commonly diamictites, most of which are of late Ordovician to early Silurian age, have been described from Nova Scotia and Newfoundland in Canada, Brittany in France and parts of Portugal and Spain and of Czechoslovakia (Robardet and Dore, 1988; Brenchley et al., 1991). Although none of these sediments are regarded by Eyles (1993) as of proven glacial origin, occasional dropstones suggest at least a seasonally cold coastline. It is interesting to note that all these areas probably broke off NW Gondwana in earlier Ordovician (Arenig) time (Pickering and Smith, 1995). All are depicted as being relatively close to Gondwana on Pickering and Smith's (1995) somewhat speculative maps, which are based on tectonic and paleomagnetic evidence, rather than any consideration of the glacial evidence. That a boundary between marine glacial sediments to the north and continental glacial deposits to the south can be recognised in North Africa (Beuf et al., 1971) suggests that all of the above occurrences may have been deposited some distance from the main continental ice-sheet(s).

In earlier work the age of the glaciation centred on late Ordovician time has been considered to range from Caradoc (early Late Ordovician) to Wenlock (middle Silurian) time. However, in a recent review Brenchley et al. (1994) suggest that there is no evidence that the lower boundary is of Caradoc age. Widespread glacio-marine diamictites deposited near the northern margin of the ice sheet are all Hirnantian in age, the youngest stage of the Ordovician (Brenchley et al., 1991), suggesting that the main ice was also of this age, although in Brazil, diamictites range into the earliest Wenlock epoch (Grahn and Caputo, 1992).

There is a large positive excursion of $\delta^{18}O$ in Hirnantian marine carbonates and $\delta^{13}C$ in Hirnantian organic and skeletal carbon associated with a eustatic sea-level rise in sections from eastern Laurentia and western Baltica (Brenchley et al., 1994). The isotopic values returned to more negative values by earliest Silurian time. These excursions are typical of what is to be expected during global as opposed to local glaciation and independently support the view that widespread Ordovician glaciation was short-lived and may have been only 0.5–1 m.y. in duration. That Silurian rocks have "normal" $\delta^{18}O$ and $\delta^{13}C$ values suggests the Silurian diamictites in Brazil (Grahn and Caputo, 1992, fig. 1) are the products of local ice centres, a view supported by the absence of Silurian glacigenic sediments elsewhere in Gondwana, with the possible exception of the Accra basin in Ghana (Talbot, 1981).

At its maximum the ice sheet is assumed to have had a distribution resembling that on Fig. 5, similar to that proposed by Vaslet (1990, fig. 11) The major changes to his distribution are the positioning of an ice lobe NW of the Amazonas basin and the insertion of an isolated ice cap to the southeast to conform to indications of ice on the Guyana and Brazilian shields (Grahn and Caputo, 1992). There are clearly many uncertainties, particularly in those areas where no Ordovician rocks are exposed, such as India, Madagascar and central and eastern Africa (Vaslet, 1990). The centroid of the distribution lies at 7°N, 16.1°E.

4. Paleomagnetic data

4.1. The geomagnetic field

The only estimators of the past positions of the geographic poles that are independent of the stratigraphic record are those provided by hot-spot positions and paleomagnetic poles. No hot-spots are known for Paleozoic Gondwana. Therefore paleomagnetism provides the only data independent of the stratigraphic record with which to compare the geographic pole positions inferred from glacial sediments.

Paleomagnetism assumes that the average of many virtual geomagnetic poles (VGPs) is closer to the geographic pole than individual VGPs. Most paleomagnetic measurements record paleomagnetic poles rather than VGPs, i.e. the pole is an average from many individual samples, smoothing the secular variation, rather than giving details of individual samples themselves. The fundamental premise for estimating geographic pole positions from paleomagnetism is that over a sufficiently long period (generally taken to be ~ 1 m.y.) the Earth's magnetic field averages to a geocentric axisymmetric dipole field, the so-called GADF model.

4.2. Late Pliocene to present-day magnetic poles

Detailed work shows that, while the GADF model is a good approximation to the long-term field, small non-dipole components persist over geologically significant periods. In particular a "far-sided" effect exists in which the pole at a given site determined from the GADF model is systematically displaced to the far side of the geographic pole when viewed from that site.

The magnitude of the effect is readily found for the past 2.5 m.y. All poles whose primary magnetisation is regarded as being of the same age as the rock age were selected from the ORACLE databases of Lock and McElhinny (1991) and McElhinny and Lock (1993). Only the best result was selected from replicate studies that had repeated measurements for the same rock unit in the same area. Poles that summarised studies already in the list were removed as far as possible, leaving an initial dataset of 313 poles. These studies are themselves averages of numerous individual measurements, commonly of mixed or reversed polarity. No distinction has been made between polarities. A further selection has been made by eliminating 75 poles that had not been magnetically tested or had undergone only partial magnetic tests, along with studies for which α_{95} was > 20°, reducing the dataset to 238 poles. No attempt was made to remove any poles with large declination and/or inclination anomalies relative to the GADF model.

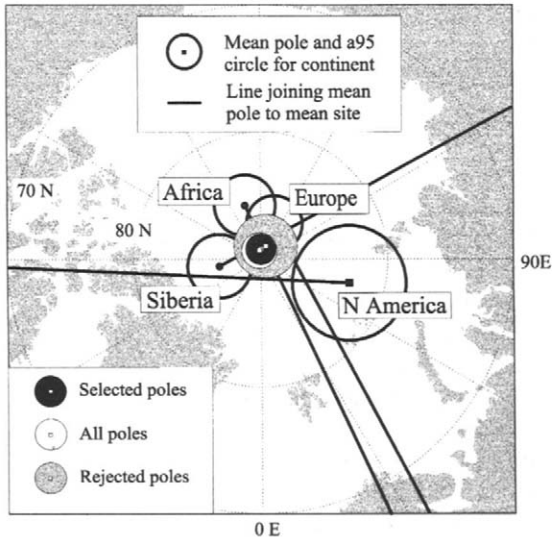


Fig. 6. The far-sided effect for the geomagnetic field over the past 2.5 m.y. Fig. 6 shows an area centred on the present North Pole, extending outwards by some 20°. The dot is the α_{95} circle for 313 poles in the age range 0–2.5 Ma; the circle is the α_{95} circle for 238 poles from this dataset that had been magnetically tested or only partially tested and whose individual α_{95} circles were > 20°; the stippled circle is for the rejected poles. Note how the α_{95} circles for all three datasets coincide within the limits of error. In addition, α_{95} circles are shown for individual continents together with a line joining the centre of the circle to the mean site of each continent. All four continental areas show the mean pole is systematically displaced to the far side of the pole as viewed from the mean site. Such an effect is likely to have existed for poles from Gondwana and given rise to additional errors in the estimate of the position of the geographic pole from paleomagnetic data.

Although there are regional variations, the mean pole of the selected list is at 89.3°N, 189.6°E with a precision $k = 46.4$ and an α_{95} of 1.4°. The pole is indistinguishable from the present spin axis (Fig. 6). The mean pole for all 313 poles is at 89.2°N, 180.0°E, with a smaller α_{95} of 1.2°, reflecting the increase in the number of poles. The mean pole of the 75 rejected poles is at 88.9°N, 160.0°E with α_{95} of 2.5° and $k = 45.1$. All three mean poles are indistinguishable both from the spin axis and from one another. This implies that the criteria used for selecting "good" data — small α_{95} and exclusion of magnetically untested or incompletely tested data — improve the precision of the data but do not significantly alter its mean value. More importantly, two independent datasets — the selected and the rejected data — reconfirm that time-averaging produces a mean pole whose position is that assumed by the GADF model. Presumably, the non-axisymmetric effects average out globally over periods of the order of 1 m.y. or so. Given the non-uniform distribution of the sites and wide range of declinations and inclinations, it is remarkable that the mean pole for the past 2.5 m.y. is indistinguishable from the spin (geographic) axis.

The size of the far-sided effect for the past 2.5 m.y. is given by the departures of the mean poles for individual continents in the age range 0–2.5 Ma (Fig. 6) from the geographic pole. The mean pole for North America (including Greenland) is at 82.8°N, 75.1°E with an α_{95} of 4.5° for 35 unselected poles; for Eurasia west of the Urals the pole is at 87.0°N, 158.9°E with an α_{95} of 2.2° for 91 unselected poles; for eastern Eurasia it is at 86.7°N, 279.5°E and an α_{95} of 2.5° for 66 unselected poles; for Africa the results are 85.6°N, 196.3°E, an α_{95} of 2.4° for 55 unselected poles. The remaining 66 poles are scattered mostly over the Southern Hemisphere and are considered inadequate to demonstrate any similar effects for southern continents. In the worst case, that of North America–Greenland, the mean paleomagnetic pole lies 7.2° beyond the geographic pole. There are several poles from tills in the North American data which have low inclinations. Their removal reduces but does not eliminate the far-sided effect. Use of the more recent database (McElhinny and Lock, in press) is unlikely to significantly affect these values.

The non-dipole effects have previously been analysed by a spherical harmonic analysis of the field (Livermore et al., 1983, 1984). The dipole field component is represented by the g_1^0 term, whose value is -1 for the present field. Livermore et al. (op. cit.) showed that the most important persistent non-dipole harmonic is due to the g_2^0, a term representing a quadrupole field. For data in the interval 0–5 Ma, the ratio, $r = g_2^0/g_1^0$ is about 0.05. r appears to have been more or less constant for 0–30 Ma, was somewhat larger (about 0.10) in earlier Cenozoic time and changed its sign at about 60 Ma to remain negative for 70–180 Ma, with values in the range of about -0.03 to -0.14. Negative values of r imply a "near-sided" effect. Such departures from the GADF model appear to be an intrinsic property of the field and cannot be eliminated by careful data selection. Ever more precise measurements simply record the fluctuations in g_2^0/g_1^0 with greater and greater precision.

From the point of view of repositioning a continent the most important parameters are the magnitudes of the errors in paleolatitude and hence in paleopole position. For convenience it is assumed that $|r| = |g_2^0/g_1^0|$ was no larger than 0.15 during the Paleozoic era. For all r the paleolatitudinal error is zero at both poles, but rapidly reaches a much more slowly varying value in mid- to low latitudes. For $r = 0.15$, the mid- to low-latitude error is about 7°. If $|r|$ was 0.15 during the Paleozoic glaciations, then the mean paleomagnetic pole inferred from the GADF model could be as much as 7° from the true position of the pole. It is not known whether the displacement would be far-sided or near-sided. Thus one way to represent the errors caused by this effect is to increase the radius of each α_{95} circle by 7°.

4.3. Paleomagnetic poles from Gondwana

Poles in the age range 490–250 Ma from Gondwana were selected from version 3.0 of the global paleomagnetic database of McElhinny and Lock (in press). This database gives all published poles up to and including 1994. As in the case of the 0–2.5 Ma data discussed above, only poles whose magnetisation ages are the same as the ages of the rocks have been used. Poles with an age uncertainty of more than 40 m.y. have been excluded. All overprinted poles or demagnetised components have been excluded, even if the age of magnetisation is thought to be well known. Where more than one independent study has been listed these have sometimes been split into individual poles instead of using the overall mean, provided each study satisfies the above criteria. The number of poles has been maximised by including poles that have not been magnetically tested, together with data from small samples and large α_{95}. Thus the "quality index", Q, in the sense of Van der Voo (1988, 1990) is closer to 3, rather than 7 in the case of the highest quality data. However, the fact that similarly untested data for the last

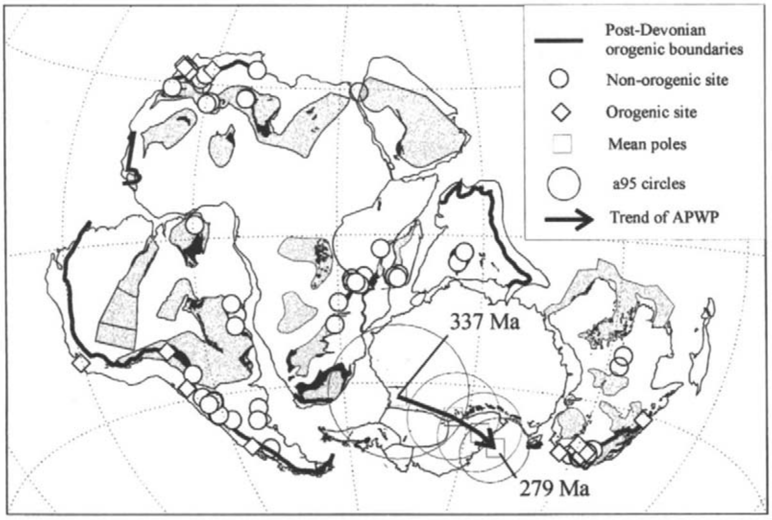


Fig. 7. Mean paleomagnetic poles and α_{95} circles for 337, 317, 297 and 279 Ma with paleomagnetic sites for the interval 370–250 Ma. The dotted circles are those with a radius of (α_{95} + 7°) to allow for the far-sided effect. Post-Devonian orogenic boundaries are shown as thick lines. Sites in orogenic areas are shown as diamonds, those in non-orogenic sites as circles.

2.5 Ma give a result indistinguishable from the best data suggests that their inclusion in the dataset will increase the scatter but not change the mean.

4.4. Poles from orogenic regions

43 poles from Gondwana are in orogenic belts (Figs. 7 and 8): 29 in Australia in Paleozoic fold belts; 3 in the Himalayan region; 6 within the Atlas fold belt in N. Africa; 2 within the Cape fold belt of southern Africa; and 4 within the Andes. Normally such poles would be excluded, but the data from Gondwana are so sparse that if they are excluded the resulting mean poles have large errors. Provided the age of the magnetisation is the same as the deposi-

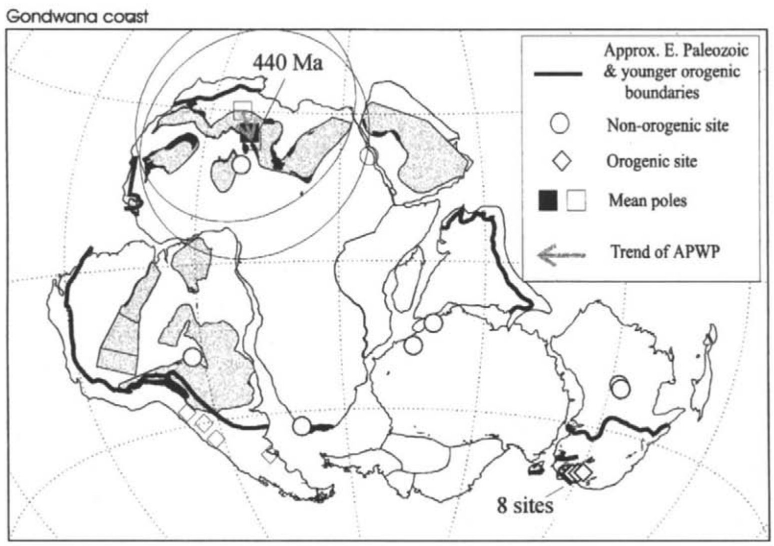


Fig. 8. Mean paleomagnetic poles α_{95} circles for 459 Ma and 433 Ma with paleomagnetic sites for the interval 490–410 Ma. The 440 Ma mean site (filled square) is linearly interpolated between 459 and 433 Ma. Early Paleozoic orogenic boundaries are shown as thick lines. Sites in orogenic areas are shown as diamonds, those in non-orogenic sites as circles.

tional or intrusive age of the rock, poles from sites in linear fold belts are probably reliable because the folds will approximate to cylindroidal folds with horizontal axes. Such poles will have been tectonically corrected by a simple rotation about a horizontal axis. Poles from the Andes, the Himalayas and the Cape Fold Belt probably approximate to this class of tectonic setting.

Poles that will give rise to significant errors will have a component of vertical rotation. Such poles will be from areas of complex folding, from tectonic terranes or areas close to major strike-slip faults. As noted by Bachtadse and Briden (1990) most of the paleomagnetically reliable Paleozoic data from Gondwana are from Australia (Embleton, 1981), many from orogenic zones. The three major pre-Mesozoic tectonic units of eastern Australia are from east to west: the New England Fold Belt (on the Tasman margin); the Sydney–Bowen basin in the middle and the Lachlan Fold Belt to the west. The two Fold Belts are believed to contain numerous terranes (Cawood and Leitch, 1985; Scheibner, 1985). Most of the pre-Permian paleomagnetically reliable Australian poles come from the Wagga–Omeo, Girilambone and Molong–Manaro "suspect" terranes of the Lachlan Fold Belt (Scheibner, 1985). It is impossible in the present state of knowledge to know whether these are far-travelled terranes or not. However, in the southern New England Fold Belt, while field evidence shows abundant evidence for the former existence of volcanic arcs and subduction complexes, provenance studies suggest that all the terranes there developed in close association with each other, rather than being exotic in origin. Thus a conservative tectonic view of both fold belts is that these terranes have been present along the edge of the Australian continent throughout Late Ordovician to early Permian but that they have episodically been deformed in such a manner as not to translate them more than, say, a few hundred kilometers along the continental margin nor to rotate them significantly about vertical axes. The simplest approach is to

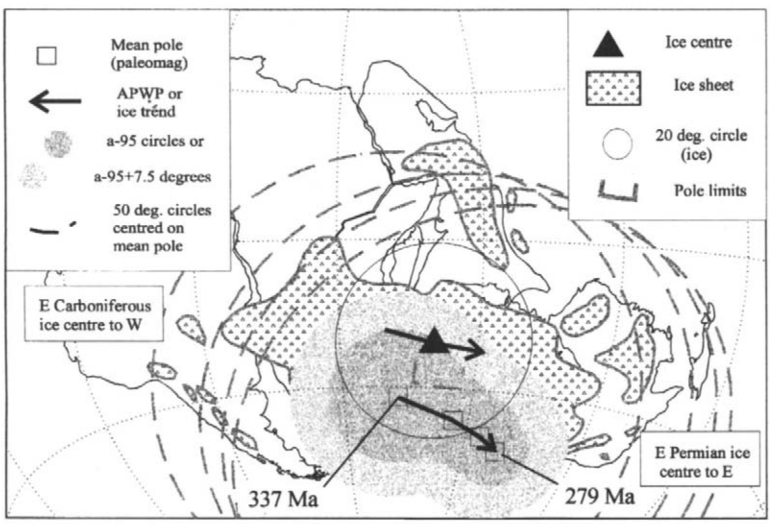


Fig. 9. Permo-Carboniferous paleomagnetic data from Fig. 7 and ice centroid data from Fig. 3. The ornamented area shows the former extent of the ice cover. The densely shaded area is that of the overlapping α_{95} circles; the lighter shaded area is the overlap of the $(\alpha_{95} + 7°)$ circles. The 20° circle centred on the Permo-Carboniferous ice centroid intersects all the $(\alpha_{95} + 7°)$ circles but does not intersect the α_{95} circle for 279 Ma. The 50° circles centred on the mean paleomagnetic poles enclose most, but not all, the inferred ice cover. If the paleomagnetic poles and ice cover are correctly shown, then for ice always to have always been poleward of 40°, the age of the ice in South America is likely to be older than that in northern Australia, as suggested by geological evidence (see text). The inferred ice cover in Oman, if it existed, is likely to belong to the older parts of the Permo-Carboniferous glaciation. See text for discussion of the "pole limits".

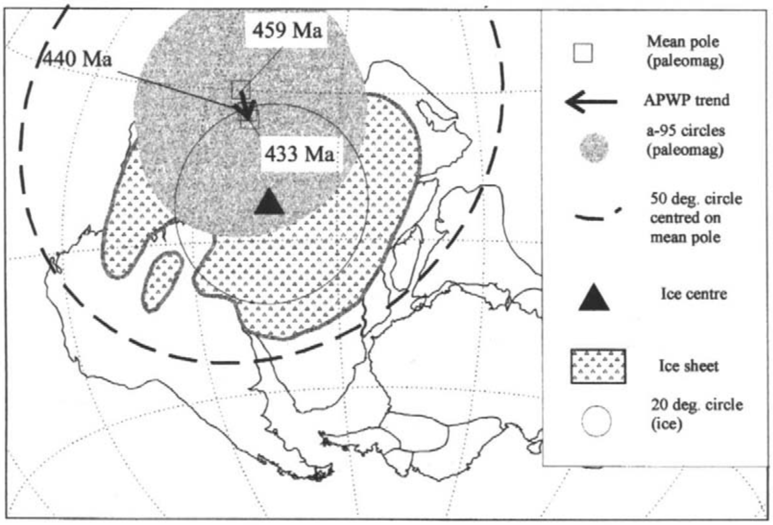


Fig. 10. Late Ordovician paleomagnetic data from Fig. 8 and ice centroid data from Fig. 5. The ornamented area shows the former extent of the ice cover. The shaded area is that of the interpolated α_{95} circle for 440 Ma. The 20° circle centred on the Late Ordovician ice centroid is very close to the mean paleomagnetic pole. The 50° circle centred on the mean paleomagnetic pole encloses all the inferred ice cover.

incorporate the southeastern Australian poles into the data but to clearly distinguish them on any pole plots so that such differences can be recognised.

Table 1
Mean South Poles for Gondwana for 60 Ma window centred on 280, 300, 320, 340, 440 and 460 Ma and Permo-Carboniferous and late Ordovician ice centroids

Average of age (Ma)	Lat	Long	α_{95}	k	Number of poles
Permo-Carboniferous:					
279	−43	69	6.8	8.5	57
297	−40	64	8.3	7.0	48
317	−37	56	9.1	6.7	42
337	−32	43	14	5.0	25
~ 290(?)	−21	50	(Ice centroid)		
Early Silurian to mid-Ordovician:					
433	24	10	23	3.2	15
440	26	10	(Interpolated)		
459	30	7	22	5.6	9
~ 440	7	16	(Ice centroid)		

Notes: Negative latitudes are degrees S; longitudes are E. k is the Fisher precision parameter. A sliding window of 60 Ma was applied to the data. Thus the age of 279 Ma is the average age of the 57 poles in the window 250 Ma to < 310 Ma.

4.5. Paleomagnetic mean poles

Because of the small number of poles in the dataset, a sliding window of 60 Ma was applied to them. The mean pole was calculated at 20 m.y. intervals (Table 1 and Figs. 7–9). The mean pole for 460 Ma includes data ranging in age from 490 Ma to > 430 Ma; that for 440 Ma includes 470 Ma to > 410 Ma data, and so on. Poles more than 90° from a mean pole were reversed. The points on the APWP are unevenly spaced, reflecting the uneven distribution of the data. The pole for 440 Ma (Figs. 8 and 10) is linearly interpolated between the mean poles at 433 Ma and 459 Ma (Table 1).

5. Comparisons with Quaternary glaciations

5.1. Permo-Carboniferous glaciation

All the α_{95} circles overlap the circle which is 20° from the ice centre (Fig. 9), with a correspondingly larger overlap of the (α_{95} + 7°) circles. The pole limits suggested by requiring ice to form south of the

40° latitude line ("pole limits" in Figs. 3 and 9) overlap the 337 and 317 Ma α_{95} circles and fall just short of the 297 and 279 Ma circles. All the (α_{95} + 7°) circles overlap the pole limit. Circles of 50° centred on the mean poles enclose all the ice when viewed as a series, but the oldest circle does not enclose the north Australian ice (present coordinates) and this is the only circle to enclose all the South American ice. The ice and the 50° circles are compatible if the South American ice was of earlier Carboniferous age and the Australian ice was younger. However, this is precisely the age trend suggested by the migration of ice centres (see p. 160).

Thus the relationship between the ice sheet and paleomagnetic data is as follows: except for the possible ice cover in Arabia, the two datasets are fully compatible with the Quaternary analogue and a normal dipole field without the need to consider the α_{95} errors, provided that there was an eastwards migration of the ice centres in time (reconstructed coordinates).

Critical to this conclusion is the nature and age of the glaciclastic sediments in Arabia. These constrain the southern limit of the "pole limits" of Fig. 3 and 9. It is unclear whether they are sub-glacial as shown on Fig. 3 or are simply glacially influenced, with a source to the S. The age of the Al Khlata Formation, the main unit in Oman, lies somewhere between late Westphalian to Sakmarian age (Levell et al., 1988), that is from about 310–270 Ma. If they are sub-glacial and late Sakmarian in age, then the paleomagnetic and ice distribution data are compatible with a Quaternary analogue only if there was a significant non-dipole component in the field, or ice extended significantly equatorwards of 40°. Whatever its age, the inferred ice cover of Gondwana is as asymmetric as the Pleistocene ice sheet in the northern hemisphere at the time at the last glacial maximum.

5.2. Late Ordovician glaciation

There are few paleomagnetic poles from Gondwana in the age range 410–470 Ma. Thus details of the conclusions set out below are likely to change as more data accumulate, but the overall conclusions will probably stand. The mean paleomagnetic pole lies just within the 20° circle centred on the ice centroid (Fig. 10). The inferred ice boundary lies polewards of the 40° latitude line. Thus, except for enigmatic glacigenic deposits in the Cape Fold Belt of South Africa, which could be Silurian in age (see p. 162), the Ordovician paleomagnetic and ice cover data are entirely compatible with the Quaternary analogue. They also show a similar asymmetric relation between the ice centre and the paleomagnetic pole. The errors in the pole position are so large (> 20°), that even if the glacigenic deposits of the Cape Fold Belt are sub-glacial, they lie well within the α_{95} error circle without the need to invoke non-dipole fields. The poles in the database suggest that the paleomagnetic pole also changed relatively rapidly during the late Ordovician to early Silurian interval to a location in southern Brazil which would certainly have brought the Cape Fold Belt into latitudes higher than 40°.

The ice centroid itself migrates rapidly from its latest Ordovician position in West Africa to early Silurian ice centres in Brazil (Grahn and Caputo, 1992, fig. 1). The imprecision and scarcity of paleomagnetic data preclude the detection of such a rapid movement — about 2500 km in 5 m.y. or 500 mm yr^{-1} — but such rates of change of pole position are unknown in Mesozoic or Cenozoic time, even for India.

The causes of such high rates of ice centre migration could be mostly tectonic. For example, Eyles (1993) has emphasised the importance of tectonic effects in causing glaciation. This hypothesis is examined only to the extent of suggesting that the duration and extent of faulting within Gondwana may correspond to the duration and extent of the ice distribution. The essential ingredient is evidence of faulting. In the case of the Brazilian basins the evidence is indirect. The creation of most sedimentary basins involves faulting. The Brazilian basins formed in late Ordovician time (Grahn and Caputo, 1992) implying the initiation of faulting at that time. In the case of the North African basins, there is clear evidence for widespread faulting in late Ordovician time. For example, Biju-Duval et al. (1981) state the whole of the Saharan platform underwent epirogenic uplift at the end of the Ordovician, during which many faults in the old Pan-African basement were reactivated.

General atmospheric circulation models suggest that by using appropriate values of CO_2 content and solar luminosity it is likely that a pole-centred supercontinent, such as late Ordovician Gondwana, will have winter snow cover but will be snow-free in summer (Crowley et al., 1993). Thus from a climate modelling point of view the problem of accounting for the short-lived late Ordovician glaciation is that of finding a switch that allows Gondwana to accumulate snow in summer for 1 m.y. or so and then reversing that switch. Faulting, particularly extensional faulting could provide just such a switch. Footwall uplift on a widespread fault mosaic could create an array of mountain ranges hundreds of kilometers long that might allow summer snow to accumulate and grow into an ice sheet. Once faulting had ceased, cooling of the lithosphere adjacent to the faults and accompanying erosion would lower the topography. The summer climate could revert to being snow-free. Thus the extent of the late Ordovician ice could largely be a reflection of the distribution of contemporaneous active faulting within the interior of Gondwana in areas sufficiently close to the geographic pole that the resulting relief allowed summer snow to accumulate and turn into ice. The ice centres in Brazil would reflect the continuation of active faulting into early Silurian time. Their rapid migration marks out those areas where stresses in the lithosphere had exceeded the critical value necessary for fracture, rather than corresponding to anomalously rapid changes in the location of the spin axis on Gondwana.

Faulting as a trigger for glaciation makes it unnecessary to appeal to any peculiarities in the geomagnetic field, obliquity or atmospheric composition as an explanation of the brevity and severity of this glacial period. Obviously, the rapid growth of an ice sheet will lower sea level, change the ocean circulation and affect the fauna and flora, but these effects are not the primary driving force for the glaciation, though they may enhance it.

6. Summary and conclusions

(1) The centroid of the present-day South Polar ice sheet lies about 5° from the South Pole; that of the North Polar ice sheet is about 15° from the North Pole. During the last glacial maximum the centroid was 17° from the North Pole. An upper limit of 20° for the position of the centroid relative to the pole is adopted for past glaciations.

(2) Even during the last glacial maximum, ice at or near sea level did not reach a latitude less than 40°, a value that is assumed to be the limiting latitude for past glaciations.

(3) Tillites and other glacigenic sediments show that the ice cover during the Permo-Carboniferous glaciation varied considerably. Glaciation appears to have started in the west and finished there earlier than it finished in the east. Therefore the centre of the ice sheet migrated from west to east.

(4) The ice distribution is reasonably well constrained at its western end in Brazil and South Africa and its eastern end in Australia for the 300–280 Ma interval. Smaller ice accumulations of uncertain shape existed in South America, western Antarctica, Arabia, India and adjacent areas but they are unlikely to greatly affect the centroid of the distribution, which lies in southern Africa.

(5) Apart from some uncertainties in central and southern Africa, the shape of the Late Ordovician ice sheet can be reasonably well defined, with a centroid in northwestern Africa.

(6) The Permo-Carboniferous and Late Ordovician geographic South Poles are assumed to lie within 20° of the centroids of their respective ice sheets.

(7) The position of the Permo-Carboniferous South Pole can be usefully and independently constrained from the shape of the ice sheet. The pole probably lies close to a line through the elongation of the ice sheet. If it lay significantly north of this line (reconstruction coordinates), ice would be placed at lower latitudes than 40°S. In particular, if the assumed ice in Arabia lay polewards of 40° then the South Pole cannot have lain south of the latitude line of about 30°S in Africa (present-day co-ordinates).

(8) Independent estimates of the geographic poles are given by paleomagnetic data. At the present time the mean of all paleomagnetic poles for the past 2.5 Ma is indistinguishable from the Earth's spin axis. The mean is not significantly different for data that satisfy rigorous selection criteria and those that do not: selection increases the precision of the result but does not change the mean.

(9) The mean paleomagnetic poles < 2.5 Ma for individual continents differ significantly from the

geographic pole. Four continents (North America–Greenland, western Europe, eastern Eurasia and Africa) show a consistent "far-sided" effect in which the mean paleomagnetic pole lies beyond the geographic pole when viewed from the mean paleomagnetic site. The greatest far-sided effect is for Greenland–North America, where it reaches 7.3°. A value of 7° is taken as the maximum value for past continents.

(10) Poles in the age range 490–410 Ma and 370–250 Ma on Gondwana were selected from paleomagnetic databases with ages believed by the compilers to be the same as the rock age and whose age uncertainty is less than 20 m.y. Because of the scarcity of the data and the fact that "quality" does not alter the mean of present-day poles, all poles were accepted, whether or not they had passed any magnetic tests. Poles from orogenic regions were also included. A sliding window of 60 m.y. was applied to these poles to derive a series of mean poles spanning the periods of ice deposition.

(11) For Permo-Carboniferous time, the 20° circle centred on the ice centroid overlaps all the α_{95} circles. The pole limits suggested by requiring ice to form south of the 40° latitude line overlap the 337 and 317 Ma α_{95} circles and fall just short of the 297 and 279 Ma circles. All the (α_{95} + 7°) circles overlap the pole limits. Circles of 50° centred on the mean poles enclose all the ice when viewed as a series, but the oldest circle does not enclose the north Australian ice (present coordinates) and this is the only circle to enclose all the South American ice. The ice and the 50° circles are compatible if the South American ice was of earlier Carboniferous age and the Australian ice was younger, which is the age trend suggested by the migration of ice centres.

(12) The Permo-Carboniferous ice sheet and paleomagnetic data are fully compatible with the Quaternary analogue and a normal dipole field without the need to consider the α_{95} errors, provided that there was an eastwards migration of the ice centres in time (reconstructed coordinates) and that the glaciclastic sediments in Arabia are not sub-glacial.

(13) The Late Ordovician ice sheet and paleomagnetic data are also fully compatible with the Quaternary analogue and a normal dipole field without the need to consider the α_{95} errors, provided that the glacigenic sediments in the Cape Fold Belt are not sub-glacial, or if they are, that they are Silurian rather than Ordovician in age.

(14) These results show that, provided likely errors are taken into account, the paleomagnetic and sedimentological data are entirely compatible with one another. There is no need to postulate the existence of significant low latitude (< 40°) ice at sea level for either of the major Paleozoic glaciations; nor to postulate a significant non-axial magnetic field, or a high non-dipole component in the field or low obliquity. Apart from the existence of widespread shallow marine glacial deposits, these glaciations appear to have closely resembled those in the Quaternary.

(15) The location and duration of the late Ordovician and early Silurian ice centres is speculatively related to the distribution and duration of contemporaneous extensional faulting. Such faulting could provide the topographic trigger necessary to convert the snow-free summer climate in the interior of a pole-centred supercontinent into one in which sufficient summer snow accumulated to form ice. The cessation of faulting and cooling of the lithosphere adjacent to the faults, together with erosion, could have lowered the topography sufficiently to allow the climate to revert to its previous snow-free summer mode.

Acknowledgements

The author thanks J.F. Harper, M.W. McElhinny, K. Pickering and J.D.A. Piper for helpful comments and criticisms, and M.J. Hambrey for making his tillite data available, although it was in fact not used in this paper and A. Hallam and R. Van der Voo for reviews. Victoria University of Wellington, New Zealand is thanked for a Visiting Fellowship and the University of Cambridge for providing travel expenses. Department of Earth Sciences contribution number 4738.

References

Astini, R.A., Benedetto, J.L. and Vaccari, N.E., 1995. The early Paleozoic evolution of the Argentine Precordillera as a Laurentian rifted, drifted, and collided terrane: a geodynamic model. Bull. Geol. Soc. Am., 107: 253–273.

Bachtadse and Briden, J.C., 1990. Paleomagnetic constraints on the position of Gondwana during Ordovician to Devonian time. In: W.S. McKerrow and C.R. Scotese (Editors), Paleozoic Paleogeography and Biogeography. The Geological Society Publishing House, Bath, vol. 12, pp. 43–48.

Bell, C.M., 1981. Soft-sediment deformation of sandstone related to the Dwyka glaciation in S. Africa. Sedimentology, 28: 321–329.

Beuf, S., Biju-Duval, B., de Charpal, O., Rognon, P., Gariel, O. and Bennacef, A., 1971. Les Gres du Paleozoique Inferieur au Sahara. Inst. Fr. Petrol., Editions Technipresse, 18, 464 pp.

Biju-Duval, B., Deynoux, M. and Rognon, P., 1981. Late Ordovician tillites of the Central Sahara. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 99–107.

Brenchley, P.J., Marshall, J.D., Carden, G.A.F., Robertson, D.B.R., Long, D.G.F., Meidla, T., Hints, L. and Anderson, T.F., 1994, Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period. Geology, 22: 295–298.

Brenchley, P.J., Romano, M., Young, T.P. and Storch, P., 1991, Hirnantian glaciomarine diamictites—evidence for the spread of glaciation and its effect on Ordovician faunas. Geol. Surv. Can. Pap., 90-9: 325–336.

Caputo, M.V., 1985. Late Devonian glaciation in South America. Palaeogeogr. Palaeoclimatol. Palaeoecol., 51: 291–317.

Caputo, M.V. and Crowell, J.C., 1985. Migration of glacial centers across Gondwana during Paleozoic Era. Bull. Geol. Soc. Am., 96: 1020–1036.

Cawood, P.A. and Leitch, E.C., 1985. Accretion and dispersal tectonics of the southern New England Fold belt, eastern Australia. In: D.G. Howell (Editor), Tectonostratigraphic Terranes of the Circum-Pacific Region, vol. 1. Earth Science Series. Circum-Pacific Council for Energy and Mineral Resources, Houston, Texas, pp. 481–492.

Choubert, G. and Faure-Muret, A., 1976. Geologic World Atlas. United Nations Educational, Scientific and Cultural Organization, Paris, 17 sheets.

Crowell, J.C., 1983. Ice ages recorded on Gondwanan continents. Trans. Geol. Soc. S. Afr., 86: 237–261.

Crowell, J.C., Suarez-Soruco, R. and Rocha-Campos, A.C., 1981. The Silurian Cancanri (Zapla) Formation of Bolivia, Argentina and Peru. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 902–907.

Crowley, T.J., Baum, S.K. and Kim, K.Y., 1993. General-circulation model sensitivity, experiments with pole-centred supercontinents. J. Geophys. Res., 98: 22,597–22,610.

Destombes, J., 1981. Hirnantian (Upper Ordovician) tillites on the north flank of the Tindouf Basin, Anti-Atlas, Morocco. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 84–88.

Deynoux, M., 1985. Terrestrial or waterlain glacial diamictites? Three case studies from the Late Precambrian and Late Ordovician glacial drifts in S. Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol., 51: 97–142.

Deynoux, M. and Trompette, R., 1981. Late Ordovician tillites of the Taoudeni Basin, West Africa. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 89–96.

Embleton, B.J.J., 1981. a review of the paleomagnetism of Australia and antarctica. In: M.W. McElhinny and D.A. Valencio (Editors), Paleoreconstruction of the Continents, Vol. 2. Am. Geophys. Union, Geodyn. Ser., Washington D.C., pp. 77–92.

Eyles, N., 1993. Earth's glacial record and its tectonic setting. Earth-Sci. Rev., 35: 1–248.

Grahn, Y. and Caputo, M.V., 1992. Early Silurian glaciations in Brazil. Palaeogeogr. Palaeoclimatol. Palaeoecol., 99: 9–15.

Hambrey, M.J., 1985. The Late Ordovician–Silurian glacial period. Palaeogeogr. Palaeoclimatol. Palaeoecol., 51: 273–289.

Hambrey, M.J. and Harland, W.B., 1981. Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, 1004 pp.

Hambrey, M.J. and Kluyver, H.M., 1981. Evidence of Devonian or Early Carboniferous galciation in the Agades region of Niger. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 189–190.

Jin, X., 1994. Sedimentary and palaoegeographic significance of Permo-Carboniferous sequences in western Yunnan, China. Sonderveroff. Geol. Inst. Univ. Koln, 99: 1–136.

Levell, B.K., Braakman, J.H. and Rutlen, K.W., 1988. Oil-bearing sediments of Gondwana glaciation in Oman. Am. Assoc. Petrol. Geol. Bull., 72: 775–796.

Livermore, R.A., Vine, F.J. and Smith, A.G., 1983. Plate motions and the geomagnetic field. I: Quaternary and Late Tertiary. Geophys. J. R. Astron. Soc., 73: 153–171.

Livermore, R.A., Vine, F.J. and Smith, A.G., 1984. Plate motions and the geomagnetic field. II: Jurassic to Tertiary. Geophys. J. R. Astron. Soc., 79: 939–961.

Lock, J. and McElhinny, M.W., 1991. The global paleomagnetic database: design, installation and use with ORACLE. Surv. Geophys., 12: 317–491.

McElhinny, M.W. and Lock, J., 1993. Global paleomagnetic database supplement number one: update to 1992. Surv. Geophys., 14: 303–329.

McElhinny, M.W. and Lock, J., in press. Global paleomagnetic database supplement number 2. Surv. Geophys.

Metcalfe, I., 1992. Ordovician to Permian evolution of Southeast Asian terranes: NW Australian Gondwana connections. In: B.D. Webby and J.R. Laurie (Editors), Global Perspectives on Ordovician Geology. Balkema, Rotterdam, p. 293.

Peltier, W.R., 1994. Ice age paleotopography. Science, 265: 195–201.

Pickering, K.T. and Smith, A.G., 1995. Arcs and backarc basins in the Early Paleozoic Iapetus Ocean. Island Arc, 4: 1–67.

Ramos, V., Jordan, T., Allmedinger, R., Mpodozis, C., Kay, S.M., Cortes, J. and Palma, M., 1986. Paleozoic terranes of the central Argentine–Chilean Andes. Tectonics, 5: 855–880.

Robardet, M. and Dore, F., 1988. the late Ordovician diamictic formations from southwestern Europe: North Gondwana glaciomarine deposits. Palaeogeogr. Palaeoclimatol. Palaeoecol., 66: 66: 19–31.

Rocha-Campos, A.C., 1981a. Late Devonian Curua Formation, Amazon Basin, Brazil. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 888–891.

Rocha-Campos, A.C., 1981b. Middle–Late Devonian Cabecas Formation, Parnaiba Basin, Brazil. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge Univrsity Press, pp. 892–895.

Rocha-Campos, A.C., 1981c. Late Ordovician(?)–early Silurian Trombetas Formation, Amazon basin, Brazil. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 896–898.

Rust, I.C., 1981. Early Palaeozoic Pakhuis Tillite, South Africa. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 113–119.

Scheibner, E., 1985. Suspect terranes in the Tasman Fold belt system, eastern Australia. In: D.G. Howell (Editor), Tectonostratigraphic Terranes of the Circum-Pacific Region, vol. 1. Earth Science Series. Circum-Pacific Council for Energy and Mineral Resources, Houston, Texas, pp. 493–514.

Scotese, C.R. and Barrett, S.F., 1990. Gondwana's movement over the South Pole during the Palaeozoic: evidence from lithological indicators of climate. Mem. Geol. Soc. London, 12: 75–86.

Smith, A.G. and Hallam, A., 1970, The fit of the southern continents. Nature, 225: 139–144.

Talbot, M.R., 1981. Early Palaeozoic(?) diamictites of south-west Ghana. In: M.J. Hambrey and W.B. Harland (Editors), Earth's Pre-Pleistocene Glacial Record. Cambridge University Press, pp. 108–112.

Van der Voo, R., 1988. Paleozoic paleogeography of North America, Gondwana, and intervening displaced terranes: comparisons of paleomagnetism with paleoclimatology and biogeographical patterns. Bull. Geol. Soc. Am., 100: 311–324.

Van der Voo, R., 1990, Phanerozoic paleomagnetic poles from Europe and North America and comparisons with continental reconstructions. Rev. Geophys., 28: 167–206.

Vaslet, D., 1990. Upper Ordovician glacial deposits in Saudi Arabia. Episodes, 13: 147–161.

Veevers, J.J., 1984. Phanerozoic History of Australia. Clarendon Press, Oxford, 418 pp.

Veevers, J.J. and Powell, C.M., 1987. Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive–regresive depositonal sequences in Euramerica. Bull. Geol. Soc. Am., 98: 475–487.

Visser, J.N.J., 1989. The Permo-Carboniferous Dwyka formation of southern Africa: Deposition by a predominanly subpolar marine ice sheet. Palaeogeogr. Palaeoclimatol. Palaeoecol., 70: 377–391.

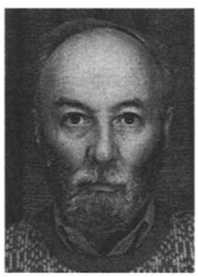
Wegener, A., 1924. The Origin of Continents and Oceans (English translation). Methuen, London, 212 pp.

Williams, G.E., 1991. Milankovitch-banded cyclity in bedded halite deposits contemporaneous with Late Ordovician–Early Silurian glaciation, Canning Basin, Western Australia. Earth Planet. Sci. Lett., 103: 143–155.

Williams, G.E., 1993. History of the Earth's obliquity. Earth-Sci. Rev., 34: 1–45.

Williams, G.E., 1994. The enigmatic Late Proterozoic glacial climate: an Australian perspective. In: M. Deynoux, J.M.G. Miller, E.W. Domack, N. Eyles, I.J. Fairchild and G.M., Young (Editors), Earth's Glacial Record. Cambridge University Press, pp. 146–164.

Wopfner, H., 1991. Extent and timing of the late Palaeozoic glaciation in Africa. Sonderveroff. Geol. Inst. Univ. Koln, 82: 447–453.



Alan G. Smith. B.A. (Cambridge) 1958; Ph.D. (Princeton) 1963. Lecturer, Department of Earth Sciences, University of Cambridge. Fellow, St. John's College, Cambridge.